Battery Technology for Data Centers: VRLA vs. Li-ion

White Paper 229

Revision 0

by Victor Avelar
Martin Zacho

Executive summary

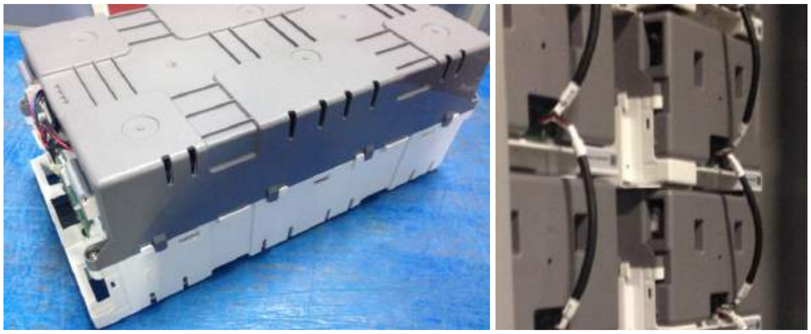
Lithium-ion battery prices have decreased over the years and are now becoming a viable option for data center UPS. This paper provides a brief overview of li-ion batteries in comparison to VRLA batteries for static UPS applications, including optimal chemistries and technologies. A 10-year total cost of ownership (TCO) analysis is provided showing li-ion is 39% less than VRLA despite their capital cost premium. A sensitivity analysis reveals the TCO drivers. Finally we discuss li-ion batteries for retrofit and new UPS applications and the effect of temperature on battery life, runtime, and cooling.

Introduction

Lithium-ion (li-ion) batteries have been used commercially for over 20 years in various applications[1]. Why then have they not been commonly adopted as batteries for static[2] data center UPSs? The answer lies in the fact that, like all other applications, li-ion cells[3] weren't available that provided UPS vendors with the right balance of price, energy density, power, safety, and reliability for static UPS applications. However, advancements in li-ion chemistries and technologies over the last 10 years have provided UPS vendors with realistic options. These advancements have largely been due to requirements set forth by the electric vehicle industry. **Figure 1** shows an example of a li-ion battery for a 3-phase UPS application.

Figure 1

Li-ion battery module for 3-phase UPS applications (left) and multiple modules connected in a cabinet



Li-ion batteries do offer legitimate benefits over VRLA (valve-regulated lead-acid) including:[4]

- Fewer battery replacements (perhaps none) required over the life of the UPS eliminates the risk of downtime posed by battery replacement
- About three times less weight for the same amount of energy
- Up to ten times more discharge cycles depending on chemistry, technology, temperature, and depth of discharge
- About four times less self-discharge (i.e. slow discharge of a battery while not in use)
- Four or more times faster charging, key in multiple outage scenarios

However, li-ion batteries also have two main drawbacks compared to VRLA:

- About two to three times more capex for the same amount of energy due to higher manufacturing cost and cost of required battery management system
- Stricter transportation regulations

This paper provides a brief overview of li-ion battery characteristics compared to VRLA. We then analyze the capital cost, operational cost, and total cost of ownership (TCO) between these two battery types. We discuss li-ion batteries for retrofit and new static UPS applications. Finally, explain the effect of temperature on battery life, runtime, and cooling.

[1] http://www.sonyenergy-devices.co.jp/en/keyword/ (last accessed on 2/28/16)

[2] This paper applies specifically to static UPS (e.g. double-conversion or delta-conversion). For information on this topic, see White Paper 1, *The Different Types of UPS Systems*.

[3] Note that the term "cell" refers to the smallest building block of a battery. Batteries are composed to two or more cells and they are packaged according to specific applications such as for use with UPS.

[4] http://batteryuniversity.com/learn/article/whats_the_best_battery (last accessed on 2/28/16)

Li-ion battery overview

At a general level, there are some common characteristics with all lithium-ion cells. For example, they are all rechargeable, they all use electrolyte, and lithium ions move between the electrodes. However, some specific characteristics depend on the chemistry and technology. The chemistry refers to the elements that result in a chemical reaction that charges and discharges the cell. The chemistry determines the cell voltage. Technology refers to other design characteristics (i.e. electrode thickness, electrolyte composition, coatings, additives, etc.) that ultimately determine the amount of energy (watt-hours), power (watts), energy density (watt-hours/kg), power density (watts/kg), service life, impact of temperature, stability, and a host of other characteristics.

The following sections provide a brief overview of some key li-ion characteristics and how they compare with VRLA batteries in static UPS applications. White Paper 231, *FAQs for Using Lithium-ion Batteries with a UPS*, provides more information on these characteristics.

Optimal chemistry

UPS applications require batteries that can provide a large amount of power capacity for 5-10 minutes. Therefore, UPS applications require li-ion chemistries and technologies that can supply a large amount of current in a short amount of time while maintaining a safe internal cell temperature. Compared to lead-acid chemistry, li-ion chemistries provide higher energy and power per unit weight, typically referred to as energy density (Wh/kg) and power density (W/kg).

Energy vs. Power

Energy (measured in watt-hours) is how long power (measured in watts) is supplied to a load. The following example explains this difference.

Battery power (W) = volts x amps. If a battery system supplies 100 volts at 10 amps, it can support 1,000 W of load.

Battery energy (Wh) = power x hours. If a battery system supplies 1,000 watts to a load for 6 minutes (0.1 hours), it supplies 100 Wh of energy.

Power cells vs. energy cells

As stated above, UPS applications require that batteries supply a large amount of current and power in 5-10 minutes. In this regard, a key distinction between li-ion and VRLA batteries is how much of the battery's energy capacity remains after the 5-10 minutes of runtime.

- A power cell is designed to provide a relatively large amount of power in a short amount of time while using nearly all of the battery's energy capacity. In a UPS application for example, a power battery solution could provide 1-2 minutes of runtime at full load while discharging about 80% of the battery energy capacity.
- An energy cell is designed to provide a relatively small amount of power over a long period of time. In a UPS application, an energy battery solution could provide the same amount of power over the same amount of time (as above) but will only discharge a 10-30%[5] of the battery's energy capacity.

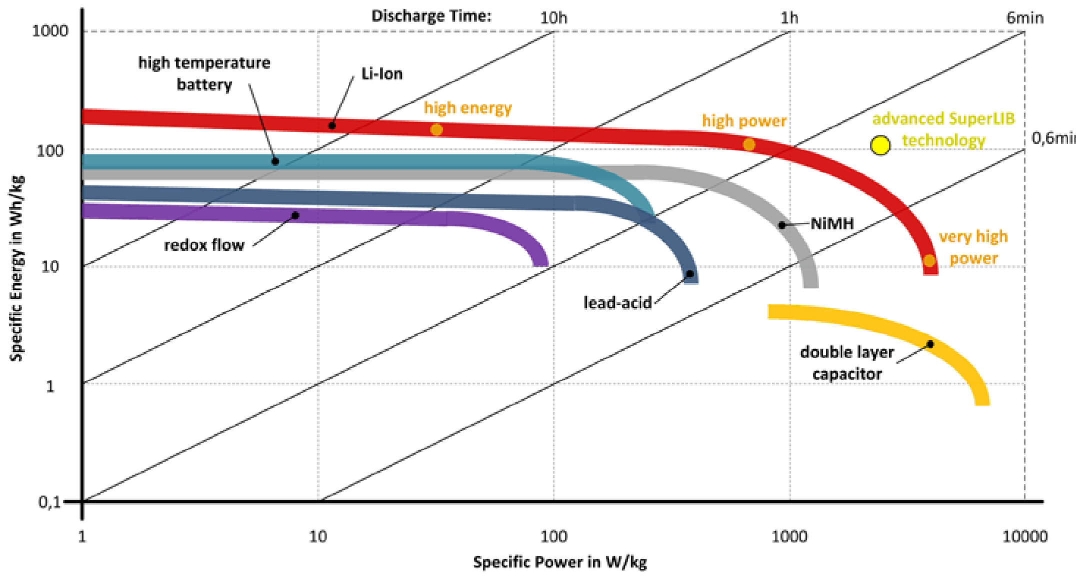
  This basically means that for this application, an energy battery solution is oversized (in energy) and will likely provide much more runtime than required. Depending on the price of the energy cell relative to the price of the power cell, it could be less expensive to use an oversized energy battery solution in a UPS application, rather than a rightsized power battery solution. **Figure 2** illustrates the relationship between energy and power for various energy storage technologies along with the corresponding impact on runtime. The downward curve for each of the lines represents the limitation of the battery to supply its full energy capacity at shorter runtimes. Note the relative positions of lead acid and li-ion for both energy density and power density.

A key conclusion is that li-ion batteries can be designed as power cells or energy cells. Conversely, VRLA battery chemistry and technology limit their design solely as energy cells.

[5] Figure 7, http://www.altenergymag.com/content.php?post_type=1884 (last accessed on 2/28/16)

Figure 2

Chart showing relationship between energy and power density also known as a Ragone plot



Source: http://www.superlib.eu/index.php?spid=en&site=preview&id=020000

Lifetime

How long a battery lasts before you need to replace it is what really matters when it comes to battery lifetime. However, it's important to understand the different metrics suppliers use to measure lifetime. Of particular importance is **service life**. This is the estimated time a battery will last before it reaches 80% of its energy capacity, the typical definition of end of life for batteries. Service life assumes the battery is operating under "real world" conditions for a stated application and is therefore highly variable. In contrast, **calendar life** is the estimated time a battery will last if it were to remain trickle charged for its entire life with no power outages at a specified temperature, usually 25°C (77°F). VRLA batteries have a service life in the range of 3-6 years whereas li-ion batteries can have a service life upwards of 10 years (estimated using accelerated life testing). Note that it will be several years before data on actual service life becomes available for newer li-ion batteries, however, some li-ion batteries offer warranties in the 10 year range as a hedge against the lack of service data.

Footprint

Due to the higher energy densities of li-ion batteries, they are much smaller in terms of footprint or volume compared to VRLA. This space savings is especially attractive to colocation data centers or data centers with high real estate costs.

Weight

Similar to footprint, the higher energy density of li-ion also contributes to its lighter weight compared to VRLA. Weight contributes to increased transportation costs.

Battery monitoring

Battery monitoring systems (BMS) are usually an add-on for traditional VRLA battery solutions. Some data center operators buy a BMS to prolong the life of the battery system. However, li-ion batteries come with a BMS by default because these batteries require full control of charging and discharging to prevent unsafe temperatures inside the li-ion cells.

Safety

Safety is top of mind when it comes to batteries especially when it comes to li-ion batteries. The important thing to remember about UPS applications is that UPS vendors need to work closely with reputable li-ion vendors to find the best combination of chemistry, technology, cell packaging, and battery management for specific

UPSs. See White Paper 231, *FAQs for Using Lithium-ion Batteries with a UPS*, for more information on safety hazards.

Regulations
There are various regulations around shipping any kind of battery including li-ion or VRLA. These shipping regulations tend to be stricter with li-ion chemistries due to the higher energy densities and higher volatility of certain chemistries.

Financial analysis

Using total cost of ownership as a metric is gaining traction in certain data center investments like cooling system economizer modes and UPS batteries. In the case of li-ion batteries, certain power cell chemistries and technologies present a favorable TCO over a 10 to 15 year period compared to VRLA batteries. This happens to be the typical life span range of a UPS before replacement is needed.

Some li-ion cost studies are available, but are not entirely useful for various reasons:

- They are focused on electric vehicle or long-runtime applications which require energy cells as opposed to power cells, ideal for UPS applications.
- They compare the cost of competing li-ion batteries and not to VRLA batteries.
- They don't provide specific li-ion chemistries and technologies specified for UPS applications.
- They focus on capital cost rather than TCO.

Lacking previous power cell cost studies for UPS applications, we relied on data provided by power cell manufactures for two specific 3-phase UPS families; Symmetra MW and Galaxy. The following sections analyze the capital expense, operational expense, and TCO over 10 years for a 1MW UPS application.

Assumptions

Table 1 provides a list of battery attributes relevant to this TCO analysis.

Table 1

Battery attributes used in TCO analysis

Battery attribute	VRLA	Li-ion
Chemistry	Lead-acid	LMO/NMC
Rated power capacity	1 MW	1 MW
Runtime at 25°C (77°F)	6 minutes	6 minutes
Calendar life at 25°C (77°F)	5 years	17 years
Battery service life at 25°C (77°F)	4 years	12 years
Battery footprint	5.4 m^2 (59 ft^2)	2.2 m^2 (23 ft^2)
Battery weight	11,340 kg (25,000 lbs)	2,767 kg (6,100 lbs)
Fixed losses from trickle charging (as % of rated UPS capacity)	0.2%	0.1%
Battery materials cost	$0.06/W	$0.12/W
Battery management system cost	Incl. in battery cost	Incl. in battery cost

Table 2 provides a list of the assumptions used for this analysis.

Table 2

Assumptions used in TCO analysis

Assumption	VRLA	Li-ion
UPS load	100%	100%
UPS service life	10 years	10 years
Operating temperature	25°C (77°F)	25°C (77°F)
Years at which batteries are refreshed before UPS life	Year 4 & 8	Not required
Electric utility cost	$0.15/kWh	$0.15/kWh
Monthly building lease cost	$32/m^2 ($3/ft^2)	$32/m^2 ($3/ft^2)
Battery room area (includes service clearance)	18 m^2 (196 ft^2)	9.5 m^2 (102 ft^2)
Battery installation	$0.012/W	$0.012/W
Battery transportation cost 322 km (200 miles) away	$0.55/kW0	$.37/kW
Battery maintenance	10%	1.5%
Cooling consumes 0.33 kW of energy for every 1 kW of heat rejected	0.33 kW/kW	0.33 kW/kW
Cost of capital	5%	5%

Capital expense

The initial battery expense, at year 0, includes the battery material costs, installation costs, and transportation costs. **Table 3** breaks down the capital expense for both battery solutions.

Table 3

Capital expense breakdown

Capital expense	VRLA	Li-ion	% change
Battery material costs	$60,000	$120,000	Li-ion 100% more capex than VRLA
Installation cost	$12,000	$12,000	Li-ion 0% more capex than VRLA
Transportation cost	$549	$366	Li-ion 33% less capex than VRLA
TOTAL	$72,549	$132,366	Li-ion 82% more capex than VRLA

Operational expense

The operational battery expenses start at year 1 and continue till year 10. Battery maintenance, space lease, and energy costs are incurred every year, while battery refresh costs are incurred at year 4 and 8. **Table 4** breaks down the operational expense for both battery solutions.

There are two types of energy losses from battery charging; fixed losses from trickle charging the battery and transient losses from discharging or charging the battery after a power outage. The energy cost in this analysis includes the fixed losses of steady state charging as well as the cooling energy required to reject the heat energy of these losses. However, more analysis is needed to better understand the effect of transient battery events on cooling requirements. The heat capacity of the battery solution plays a large role in determining the heat removal capacity of the cooling system as well as the cooling energy consumption. The TCO analysis in this paper will be updated with the effect of transient events once this analysis is complete. **Table 4** breaks down the operational expense for both battery solutions.

Table 4

Operational expense breakdown

Operational expense	VRLA	Li-ion	% change
Battery maintenance	$46,330	$13,899	Li-ion 70% less opex than VRLA
Space least cost	$54,597	$28,368	Li-ion 48% less opex than VRLA
Energy cost	$26,989	$13,495	Li-ion 50% less opex than VRLA
Battery refresh	$108,790	$0	Li-ion 100% less opex than VRLA
TOTAL	$236,706	$55,762	Li-ion 76% less opex than VRLA

TCO

The 10-year TCO considers the capital and operational expenses above. The li-ion battery solution has a 39% lower 10-year TCO than the VRLA solution. The cash flows for this analysis result in a simple payback of 3.4 years to breakeven from the higher li-ion capital expense at year 0. **Table 5** breaks down the TCO for both battery solutions.

Table 5

TCO breakdown

TCO	VRLA	Li-ion	% change
Capital expense	$72,549	$132,366	Li-ion 82% more capex than VRLA
Operational expense	$236,706	$55,762	Li-ion 76% less opex than VRLA
TOTAL	$309,255	$188,128	Li-ion 39% less TCO than VRLA

Sensitivity analysis

We independently varied 12 cost factors to assess the variability and magnitude of change they have on TCO. For example, we varied VRLA service life from 2 to 7 years which resulted in changes in TCO savings ranging from 0.8% to 15.5%. Based on this sensitivity analysis the factors that most influence the TCO comparison between VRLA and li-ion are:

- VRLA service life
- UPS service life
- VRLA $/W
- Li-ion $/W
- Battery room area
- VRLA maintenance
- Cost of capital

It's important to note that while each of these can independently cause a significant change in TCO between both battery solutions, a combination of a few of these factors can swing a decision to adopt one or the other. In particular, the VRLA service life, being shorter than li-ion, becomes a big lever in combination with the UPS service life. For example, a VRLA life of 4 years in combination with a UPS life of 8 years results in only a single battery refresh. However, increasing the UPS life by only 2 years results in two VRLA battery refreshes, a significant change in TCO in favor of li-ion.

Battery pricing obviously plays a strong role in this TCO model but the VRLA $/W factor is more important than the li-ion cost because of the number of battery refreshes multiplies the effect of a lower or higher VRLA price. In fact any cost component with a sizable annual cost plays are large role in deciding on one battery solution of another. This is why battery room area and VRLA maintenance (higher than li-ion) are strong TCO drivers. Finally, since it is evident that these operational cash flows strongly influence the TCO, it is understandable that the cost of capital can either minimize the cash flows (e.g. 20% cost of capital rate) or maximize the cash flows (0% cost of capital rate), which decreases or increases the TCO.

For further insight on TCO sensitivity see TradeOff Tool 19, Lithium-ion vs. VRLA Battery Comparison Calculator. This tool allows you to change various inputs such as UPS service life and see the impact they make on TCO of the two battery types.

Retrofit and new UPS applications

If you choose to use li-ion batteries for your static UPS application, there are a few important considerations depending on if you're retrofitting the battery solution of an existing UPS or buying a new UPS. This assumes a static UPS life expectancy of about 10-15 years, VRLA battery service life of 3-6 years, and li-ion battery service life of 10 years or more.

There are three possible scenarios when deciding to retrofit the VRLA batteries of an existing UPS:

1. The UPS is operating in the early part of its lifecycle
2. The UPS is operating near the middle of its lifecycle
3. The UPS is operating at the end of its lifecycle

For a UPS in the **early part of its lifecycle**, generally less than 5 years old, it may make sense to retrofit the VRLA batteries with li-ion batteries because the li-ion batteries will likely reach end-of-life at about the same time as the UPS.

For a UPS **near the middle of its lifecycle**, generally 5-10 years old, it makes sense to refresh the VRLA batteries. Retrofitting the VRLA batteries with li-ion at this phase in the UPS life may not make economical sense given that the li-ion batteries will outlive the useful life of the UPS by more than 5 years. However, as the price of li-ion batteries decrease over the coming years, the economics may in fact favor retrofitting the VRLA with li-ion batteries.

For a UPS **near the end of its lifecycle**, generally more than 10 years old, it may make sense to replace the entire UPS with a new UPS that uses li-ion batteries. This decision really depends on the cost of keeping and maintaining an old UPS (i.e. service contracts, spare parts, etc.) compared to the cost of a new solution.

For cases where you're considering retrofitting VRLA for li-ion batteries, be aware that li-ion batteries are not a "drop-in" replacement for VRLA batteries. Even if a li-ion battery solution had the same nominal voltage as an existing VRLA solution, the UPS may need upgraded firmware and/or hardware. This is because, among other things, the battery charging characteristics may change, the runtime formula may be different, and the runtime estimate may be incorrect. In addition to this, the vendor may need to integrate the battery monitoring system with the UPS. These and other factors are all things that the UPS vendor must account for when offering a li-ion battery solution for specific UPS models.

Buying a new UPS is the most straightforward scenario given that the UPS vendor has effectively integrated the li-ion technology with the UPS. The integration between the UPS and the li-ion BMS is heavily dependent on the operation of the BMS which is variable from vendor to vendor. Eventually standards will emerge that drive consistency between the UPS and BMS from different vendors. An example of a UPS that uses li-ion batteries is shown in **Figure 3**.

Figure 3

An example of a UPS with li-ion batteries is the Galaxy VX from Schneider Electric

Effect of temperature

There are many reasons why temperature affects batteries in many different ways and some of these effects are specific to a particular chemistry. But ultimately there are three important considerations with regard to temperature, in order of importance:

- Battery service life
- Battery runtime
- Cooling energy

Battery service life

It's well proven in scientific literature that temperature affects the service life of most components and batteries are no different. The rule-of-thumb for batteries (both VRLA and li-ion) is that you decrease the battery service life by 50% for every 8-10°C (14-18°F) increase in average ambient temperature[6]. Assuming VRLA service life is 3-6 years and li-ion is on the order of 10 years, we expect higher temperatures to result in more frequent battery refreshes with VRLA compared to li-ion, within the service life of the UPS. This effect is quantified in the TCO analysis above. See White Paper 39, *Battery Technology for Data Centers and Network Rooms: VRLA Reliability and Safety*, for more information on VRLA life.

[6] http://www.cdtechno.com/pdf/ref/41_7329_0512.pdf (last accessed on 3/2/16)

Runtime

Runtime is all about a battery supplying a certain amount of current or amps (A) at a certain voltage (V). Multiply these two together and you get **power** (W) to support your IT load.

$$V \times A = \text{watts (W)}$$

Now add time to this formula and you get **energy** measured in watt-hours (Wh).

$$V \times A \times \text{time} = \text{Wh}$$

As the battery discharges, the battery output voltage decreases which means more current is required to maintain **constant power** to the load. Now the question is what happens to the runtime as the temperature increases? As temperature increases, for VRLA and li-ion batteries alike, the internal resistance decreases. Lower resistance means lower losses, which means the output voltage doesn't drop as fast, which means you pull less amps per minute out of the battery at higher temperatures then you would at lower temperatures. So why not run your batteries at higher temperatures to get more energy capacity and runtime? The answer points back to decreased battery service life. Note that this relationship of temperature and resistance holds true for battery charging as well.

As explained previously, there are two types of li-ion cells; power cell and energy cells. These do behave differently as a function of temperature because power cells inherently have a lower resistance than energy cells. So for the same time on battery, the energy cell internal temperature is higher than the power cell. While discharging, energy cells can experience an internal temperature rise of 30°C (54°F). This isn't a problem if the battery room temperature is at 25°C (77°F), but if the battery room is at 40°C (104°F) the same 30°C (54°F) temperature rise may cause the battery monitoring system to shut off the battery to prevent irr. Despite this behavior at relatively high ambient temperatures, li-ion batteries are much better suited than VRLA batteries for operating in hotter environments due to their longer service life. Note that for VRLA batteries, temperature rise should typically be limited[7] to a temperature rise of 10°C (18°F).

Cooling

For both VRLA and li-ion there are two approaches to sizing the cooling system; size only for steady state losses (i.e. trickle charging) or size for the heat energy generated during discharge (transient losses). Transient losses are much larger than steady state losses in terms of power (kW) but the total amount of heat energy (kWh), assuming 6 minutes of runtime and 20 outages per year, is about 100 times smaller than the heat energy generated by trickle charging for a year.

Whether discharging a li-ion or VRLA battery system, the battery room temperature will increase a certain amount. If the cooling system is sized for the steady state load, it will take a longer time to bring the room temperature back to its set point (on the order of hours). How will this temporary higher temperature affect the battery system? It's clear that the effect on li-ion batteries is minimal compared to VRLA.

Based on what we know today, it makes more sense to size the li-ion battery cooling system for the steady state case. This will save on the capital cost of a higher-capacity cooling system and the increased energy cost associated with operating a

[7] http://www.cdtechno.com/pdf/ref/41_7944_0712.pdf (last accessed on 3/2/16)

larger cooling system (assuming higher fixed losses). Ultimately, because of li-ion's relatively long service life, data center operators have a few options. They can increase their battery room temperature to save energy (or remove the cooling system outright) and rely on their battery warranty[8] to ensure they reach their UPS service life without any capital outlay. Or they can cool the room to 25°C (77°F), sized for steady state losses, and incur a minimal annual energy expense.

For VRLA, the thinking is different, due to the significantly shorter service life. In the model presented in this paper, if you could extend the life of the VRLA battery by one year, by decreasing the room temperature and increasing the cooling system capacity, it would be worth incurring the additional energy operational expense and cooling system capital expense.

Conclusion

It is safe to say that Lithium-ion battery prices will continue to decrease, new chemistries and technologies will be brought to market, and improvements will be made to existing ones. With this backdrop and the analysis presented in this paper, Lithium-ion battery systems for data center UPS applications (and UPS applications in general) offer compelling benefits. While some li-ion solution prices are too high to justify switching from VRLA, there are some that present a favorable 10-year TCO with payback in less than 4 years.

About the authors

Victor Avelar is the Director and Senior Research Analyst at Schneider Electric's Data Center Science Center. He is responsible for data center design and operations research, and consults with clients on risk assessment and design practices to optimize the availability and efficiency of their data center environments. Victor holds a bachelor's degree in mechanical engineering from Rensselaer Polytechnic Institute and an MBA from Babson College. He is a member of AFCOM.

Martin Zacho is a Senior Engineer in Energy Storage Technologies at Schneider Electric, Secure Power, IT Business. He holds a Bachelor degree in Computer System Engineering from University of Southern Denmark. He started out at Schneider Electric in 2000 (American Power Conversion at the time) working with Hydrogen Fuel Cells. After 3 years he switched to firmware control and FPGA programming for the Symmetra line products. He has been involved in all aspects of energy storage technologies since 2008 with special focus on energy storage for large 3 phase UPS's. The relevant technologies being lead acid batteries, ultra-capacitors, flywheels and various lithium based technologies. He is a member of The Danish Standardization Committee regarding energy storage.

[8] This assumes the warranty allows for higher temperature environments and does not prorate the expense of a new battery system.

Resources

[The Different Types of UPS Systems](#)
White Paper 1

Battery Technology for Data Centers and Network Rooms: Lead-Acid Battery Options
White Paper 30

Battery Technology for Data Centers and Network Rooms: VRLA Reliability and Safety
White Paper 39

Lead Acid Battery Lifecycle: Terms and Definitions
White Paper 230

FAQs for Using Lithium-ion Batteries with a UPS
White Paper 231

Browse all white papers
whitepapers.apc.com

Lithium-ion vs. VRLA Battery Comparison Calculator
TradeOff Tool 19

Browse all TradeOff Tools™
tools.apc.com

Contact us

For feedback and comments about the content of this white paper:

Data Center Science Center
dcsc@schneider-electric.com

If you are a customer and have questions specific to your data center project:

Contact your Schneider Electric representative at
www.apc.com/support/contact/index.cfm